# Shear Production and Dissipation in a Stratified Tidal Flow

Stephen G. Monismith
Dept of Civil and Env. Eng.
Stanford University
Stanford, CA 94305-4020
phone (650) 723-4764 fax (650) 725-9720 email: monismit@ce.stanford.edu

Mark T. Stacey
Dept of Civil and Env. Eng.
University of California at Berkeley
Berkeley, CA 94720-1710
phone (510) 642-6776 fax (510) 642-7483 email: mstacey@socrates.Berkeley.EDU

Jon R. Burau
USGS Water Resources Division, Ca. District
6000 J Street, Placer Hall
Sacramento, CA 95819-6129
phone (916) 278-3127 fax (916) 278-3070 email: jrburau@usgs.gov

Award Number: N00014-99-1-0292
http://fluid.stanford.edu/~mbrennan/research/cut99/cut99.html

## LONG-TERM GOALS

The long term goal of this work is to understand the physics of turbulent stratified shear flows as might be found in coastal regions and estuaries where both shear and stratification are strong. It is our hypothesis that turbulence under these conditions of active generation may function in a way that is fundamentally different from weak turbulence below the thermocline (or above the bottom mixed layer) in the ocean. We anticipate that such an understanding will permit the development of accurate predictive models of turbulence dynamics for energetic coastal flows.

## OBJECTIVES

This project, carried out in conjunction with Mike Gregg of the Applied Physics Laboratory at the University of Washington, has as its objective obtaining a relatively complete set of observations of turbulence structure and variability in Suisun Cut, a tidal channel in Northern San Francisco Bay. In this region both tides and stratification are strong: typical shears might be 0.1 $s^{-1}$ with comparable buoyancy frequencies. These conditions typify coastal zone flows. Given these conditions, flows in Suisun Cut are found to have high turbulence Reynolds number over a wide range of flow stabilities. Past work, reported in Stacey et al 1999, using an Acoustic Doppler Current Profiler (ADCP) to measure turbulent Reynolds stresses however assumed that the rate of shear production of turbulent kinetic energy was in balance with turbulence dissipation. The new work will build on the Stacey et al. results by including direct measurements of profiles of turbulence dissipation rates (Gregg) and bottom stresses using Acoustic Doppler Velocimeter (ADV - Monismith/Burau) to water column ADCP derived turbulence measurements (Monismith/Burau). Moreover, the data reported in Stacey et al represented the evolution of the flow over 1 tiday day during a neap tide; in the new work, we plan up to 2 weeks of observations spanning a complete neap-spring tidal cycle. Thus, we expect to obtain a substantially more comprehensive picture of flow behavior than was previously available.

Besides improving our empirical description of these stratified shear flows, we also plan to use this data set in conjunction with Large Eddy Simulation (LES) studies of stratified turbulence to develop new (and improved) models of stratified turbulence behavior.

## APPROACH

A field experiment involving synoptic measurements of turbulence dissipation (via dissipation profilers), turbulent Reynolds stresses and production (ADCPs and ADVs), density structure (via autonomous CTDs), and sediment re-suspension (using calibrated Optical Backscatter Sensors - OBS) was carried out between the 14$^{th}$ and 27$^{th}$ of October 1999 in Suisun Cutoff in Northern San Francisco Bay. Fixed instruments were deployed by the Stanford/USGS group in the center of the channel where between the 18$^{th}$ and 26$^{th}$ of October Mike Gregg's group carried out extensive dissipation profiling and acoustic imaging.

The Stanford /USGS group used/deployed the following fixed instruments:

1. A bottom frame carrying 3 ADVs (distributed over the bottom 1m of the water column), 3 OBS (coincident with the ADV measurement volumes), 1 conductivity/temperature (CT) sensor pair, a pressure transducer, and an inclinometer. The OBS, CT and presssure sensors were connected to a single Ocean Sensors OS200 CTD. Along with the CTD, all 3 ADVs, were cabled to the surface and connected to data logging computers kept on a houseboat that was anchored nearby. Matt Brennan, a PhD student of the PI has responsibility for this data.

2. A pair of ADCPs mounted on a single frame with one ADCP looking up and one looking down were deployed to record shear stresses and turbulent kinetic energy (TKE) profiles over the entire water column. The downward looking unit was a 600 KHz workhorse unit set to sample 10cm bins in RDI's pulse-to-pulse coherent mode, mode 5. The upwards looking 1200 KHz ADCP sampled 0.25 m bins using RDI's broadband mode, mode 4 (as in Stacey et al 1999). Both ADCPs were cabled to computers on the houseboat for logging of every ping. Prof. Mark Stacey of U.C. Berkeley has taken responsibility for acquisition and initial processing of this data.

3. An ADCP (1200 KHz, mode 4, 0.25m bins) and an autonomous CTD (set to profile every 10 minutes), both mounted on the houseboat were used to measure density, sediment, velocity and stress/tke profiles over the upper 85% of the water column. Matt Brennan and the PI will be responsible for this data.

Two autonomous CTD profilers were deployed at either end of the 3km long channel to measure density profiles and hence the baroclinic pressure gradient in the cut. Additionally, two Seabird seagauge pressure recorders were also deployed at either end of the channel to record the barotropic tidal pressure gradient. Burau and Monismith will be responsible for this data.

In addition to these fixed deployments, as part of its own Bay research program, the USGS also made several month-long deployments in the larger Suisun Bay region of several ADCP and top-bottom salinity recorders. This data will provide background hydrographic data for interpretation of data taken during the intensive turbulence field experiment. Finally, also as part of a separate project (supported by the state and federal agency Cal-Fed Bay Delta Program ), on two days, October 20 and October 26, extensive ADCP/CTD transects were taken in Suisun Cutoff for about 15 hours on each day.

## WORK COMPLETED

All of the deployments discussed above were carried out and all instruments were recovered successfully. Aside from a variety of minor malfunctions, data was acquired from all of the instrumentation deployed. Since last October, analysis of the data has proceeded along three fronts:

### 1. Analysis of ADCP-derived turbulence data including density stratification.

ADCP and CTD data were processed using the methods described in Stacey et al (1999) to produce fields of velocity, density, Richardson number, stress, TKE, production, turbulence length scale, turbulence Froude number, and the activity parameter defined using the production rate,P, i.e., $P/\nu N^2$. Stacey (2000) has also developed a technique for using third moments of the beam velocities to compute an estimate of turbulence self-transport.

### 2. Analysis of mean flow time series data focussed on the mean momentum balance.

Pressure gauge, ADCP turbulent stress and mean flow data have been synthesized to test closure of the local momentum balance. We also examined parametrizations of bottom stress in terms of near-bottom mean velocities as well as depth-averaged velocities.

### 3. Analysis of bottom turbulence and sediment dynamics

ADV data has been analyzed to produce time series of turbulent velocities and fluctuating sediment concentration. The latter quantity was derived from ADV backscatter amplitude using calibrations derived from approximately 20 water samples. Interestingly, the calibration of ADV backscatter had a slightly larger value of $r^2$ than did that for the OBS sensors deployed on our instrument package.

## RESULTS

### Turbulence dynamics

The experiment was begun during a neap tide and finished during a spring tide. As a consequence, Suisun Cutoff channel went through a transition from a period of significant periodic stratification to a period of persistently well-mixed conditions . Further, the periodic stratification that occured during the neaps is not periodic on the 12-hour timescale, but rather on the 24-hour timescale. This variation is closely tied to the strong diurnal inequality seen in the tides in this estuary. During the weak ebb tides, turbulent mixing was insufficient to break down the stratification being produced through advection by the tidal currents. During the strong ebb tides in the neaps – and throughout the springs – mixing was sufficient to preserve a well-mixed water column.

This spring-neap modulation of stability is well reflected in the Richardson Number which showed that much of the early phase of the experiment was characterized by Richardson numbers well in excess of the critical value of 0.25 throughout most of the water column. As a result of this stability, turbulent shear stresses were suppressed outside of the bottom mixed layer, particularly on ebb tides, leading to a notably asymmetry in bottom stress between ebbs and floods. Interestingly, throughout this entire time, the bottom stresses (i.e., the stress measured in the bottom-most bin of the upwards-looking ADCP) can be well computed using a fixed drag coefficient of 0.0017 (referenced for comparison sake to what one would obtain from the law of the wall and the velocity measured at 1m). This is equivalent to a roughness height of 0.5 mm, suggesting that our bed was relatively smooth.

The stress and shear measurements can be used to compute the rate of TKE production, which, as a first approximation, can be taken to be equivalent to the TKE dissipation rate (something we plan to test this coming year through intercomparison of our data with that which Mike Gregg's group collected). This allows us to compute the activity parameter, $P/\nu N^2$. Despite the high stability of the flow during the neap, values of $P/\nu N^2 > 200$ (the value Gargett et al 1984 suggest is required for small-scale isotropy) were common. While the turbulence we observed was quite energetic, the turbulence Froude number $Fr_t = q/NL$ (L is the turbulence length scale derived from the measured mixing length) was often close to its critical value of 1 during much of the neap. This view of energetic, stratified turbulence is better seen in figure 1, views of both $P/\nu N^2$ and $Fr_t$ for the neap period. Analysis of this data is ongoing.

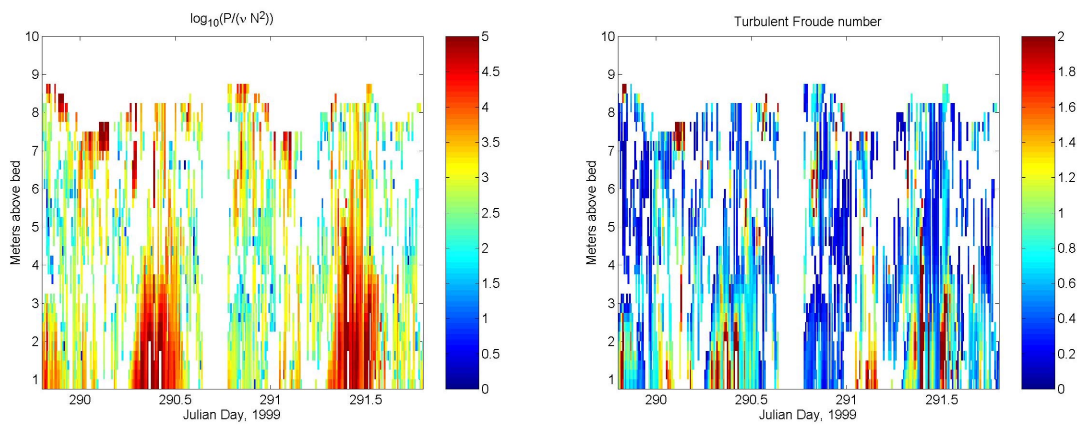


***Figure 1: $P/\nu N^2$ and $Fr_t$ observed during the neap period (white represents no data)***

**Mean Momentum balance**

The ADCP and pressure gauge data were combined to look at the depth-averaged one dimensional (no advection of momentum) along-channel momentum balance. This work showed a periodic imbalance that suggests that advection may play an important role in the overall momentum balance. Across-channel transect work done during the Suisun Cut experiment (which is being analyzed with support from the Cal-Fed Delta Restoration program) suggests that strong lateral variations in density and velocity associated with density fronts that develop through differential advection of different salinity water through the Cutoff from the large bays on either side. These flow variations may mean that the cross-channel advection of along-channel momentum is important to the overall momentum balance, a hypothesis we will test in the next period.

**Sediment dynamics**

An acoustic Doppler velocimeter (ADV) mounted 0.97 m above the bed, yielded simultaneous measurements of velocity (u,v,w) and suspended sediment concentration (c) at frequencies of 25 Hz.

Time averaging the product of the vertical velocity fluctuations (w') and the suspended sediment concentration (c') produces an estimate of the turbulent sediment flux (<w'c'>) from the bed to the water column.

While the turbulent sediment flux, was proportional to bed shear stress, the relation was not uniform in time. Turbulent sediment flux was most responsive to the Reynolds stress (<u'w'>) at the beginning of flood tides, as indicated by the steeper slope of data points from the first 2 hours of flood. The slope's steepness, which is indicative of the sediment's erodibility, was less during all other times of the tidal cycle. Several potential mechanisms may explain this asymmetry in erodibility. Flocculation of cohesive sediments is modulated by changes in the electrostatic environment set by the salinity. This would imply that sediment deposited at the end-of-ebb salinity of 8 had less shear strength than the sediment deposited at the greater end-of-flood salinity of 14. Or perhaps clams (*Potamocorbula amurensis*), which inhabit the bed in the Cutoff at densities of several thousand per square meter, are a source of bioturbation during the beginning of flood tides. They typically feed on the bed surface during ebb tides which carry a larger nutrient load from river discharge. When the tide switches to flood, they are actively digging to bury themselves into the mud. Finally, an increase in sediment concentration through advection would also increase c' and hence <w'c'>. Because the salinity enhancement of sediment shear strength has been found in laboratory experiments to be negligible above 10 (Parchure and Mehta, 1985), the first mechanism is a less likely explanation. Although the influence of clams will be impossible to quantify, an analysis of the data from sediment sampling stations along the flow streamlines may shed some light on the advection question. Whatever the mechanism, the asymmetry in erodibility combined with the bed shear asymmetry to create a mean (8 day averaging interval) landward flux of sediment of 14 $g/s/m^2$ for this experiment.

Upcoming work will include laboratory testing of the ADV's capacity to measure turbulent sediment flux and an examination of the vertical distribution of suspended sediment through out the water column.

## IMPACT/APPLICATIONS

The data collected during our experiment are intended to advance our ability to predict the structure and mixing of stratified tidal flows, including sediment resuspension and erosion. In particular, the data will be made available to the coastal physical oceanography community, and will be also be used by the PIs in collaboration with colleagues at Stanford (Koseff, Ferziger, and Street) for the development of new parametrizations of stratified turbulence closures.

## TRANSITIONS

None at this time

## RELATED PROJECTS

A STUDY OF THE STRUCTURE OF NEAR COASTAL ZONE WATER COLUMN USING NUMERICAL SIMULATION (ONR - Koseff, Ferziger and Monismith) - This work is using Large Eddy Simulation to study the physics of flow influenced by stratification and by surface waves.

CHARACTERIZATION AND MODELING OF PLUMES AND ANIMAL PLUME-TRACING IN WAVE-INFLUENCED COASTAL ENVIRONMENTS (ONR - Koseff and Monismith) - The portion of this work for which Monismith is responsible involves field experiments looking at plume dispersion and plume source in the near-shore environment. These experiments are part of the ONR Chemical Sensing in the Marine Environment Program managed by Dr. Keith Ward.

**REFERENCES**


Parchure, T.M., and Mehta, A.J., 1985, Erosion of soft cohesive sediment deposits: J. Hyd. Eng., v. 111, no. 10, p. 1308-1326.

Stacey, M.T., S.G. Monismith, and J.R. Burau, 1999 “Observations of turbulence in a partially stratified estuary,” J. Phys. Oceanog. 29 pp. 1950-1970, 1999.


**PUBLICATIONS**


Brennan, M.L., Schoellhamer, D.H., Burau, J.R. and Monismith, S.G. 2000. “Tidal asymmetry and variability of cohesive sediment transport at a site in San Francisco Bay, California”. Proceeding of the 6th International Conference on Nearshore and Estuarine Cohesive Sediment Transport Processes. (in press)

Stacey, M. T., Burau, J. R., Brennan, M. L., Lacy, J. R., Tobin, C. C. and Monismith, S. G. "Spring-Neap Variations in Stratification and Turbulent Mixing in a Partially Stratified Estuary," to appear in Proceedings of the Fifth International Symposium on Stratified Flows, IAHR, July, 2000.

Stacey, M. T., "Estimation of Turbulence Parameters using an ADCP," to appear in Proceedings of the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management, ASCE, August, 2000.